VCSEL end-pumped passively Q-switched Nd:YAG laser with adjustable pulse energy

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Abstract: A compact, passively Q-switched Nd:YAG laser utilizing a Cr^{4+}:YAG saturable absorber, is end-pumped by the focused emission from an 804 nm vertical-cavity surface-emitting laser (VCSEL) array. By changing the VCSEL operating current, we demonstrated 2x adjustability in the laser output pulse energy, from 9 mJ to 18 mJ. This energy variation was attributed to changes in the angular distribution of VCSEL emission with drive current, resulting in a change in the pump intensity distribution generated by a pump-light-focusing lens.

OCIS codes: (140.3530) Lasers Neodymium; (140.3540) Lasers, Q-switched.

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A compact, passively Q-switched Nd:YAG laser utilizing a Cr4+:YAG saturable absorber, is end-pumped by the focused emission from an 804 nm vertical-cavity surface-emitting laser (VCSEL) array. By changing the VCSEL operating current, we demonstrated 2x adjustability in the laser output pulse energy, from 9 mJ to 18 mJ. This energy variation was attributed to changes in the angular distribution of VCSEL emission with drive current, resulting in a change in the pump intensity distribution generated by a pump-light-focusing lens.</td></tr>
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1. Introduction

Recent advances in power and brightness available from VCSEL arrays [1,2] operating near 808 nm have made these sources suitable for pumping Nd:YAG solid state lasers. Compared with laser diode stacks consisting of multiple edge-emitting bars, VCSEL pumps offer the advantages of reduced tuning of wavelength with temperature, more uniform intensity distribution, simpler manufacturing and potentially higher reliability due to lower optical power density at the emitter aperture. To our knowledge, there have been no reports of VCSEL end-pumped solid state lasers. As we show here, VCSELs are particularly well suited for end-pumped of passively Q-switched lasers, where uniform pump distribution is required to achieve good beam quality and high energy extraction. Compared with active Q-switching, passive Q-switching allows more compact and lower cost lasers, since it eliminates the electro-optic Q-switch and the associated high voltage driver. These advantages are particularly important for lasers generating moderate energy(1-100 mJ) at relatively low pulse repetition frequencies (PRFs), typically required for compact, long-range, laser range-finders, laser markers and laser designators. Such passively Q-switched lasers, however, do not allow adjustment of the pulse output energy after the laser is fabricated. The stored laser energy and output pulse energy are fixed by the values of un-bleached transmission of the saturable absorber, cavity losses and the laser active cross-sectional area [3–7]. Such lack of pulse energy adjustability is particularly problematic in passively Q-switched lasers required to operate over a wide temperature range, as the change of the Nd:YAG stimulated cross-section with temperature changes the laser output pulse energy [8].

Here we describe a compact, VCSEL end-pumped, passively Q-switched Nd:YAG rod laser, and also present a simple technique for adjusting the pulse energy in such a laser. This adjustability is achieved by varying the VCSEL drive current, causing a change in its divergence characteristics. When the VCSEL emission is focused by a lens onto the Nd:YAG rod, this change in divergence produces a variation in the size and intensity profile of the focused pump spot, which in turn alters the active area in the laser and hence its pulse energy. Previously, pulse energy variation in passively Q-switched lasers was observed under CW pumped, high PRF conditions, and attributed to several phenomena, including thermal lensing, incomplete recovery of saturable absorber between pulses, and pump-induced bleaching of saturable absorber [9–11]. None of these effects, however, played a significant role in our experimental conditions of low PRF, low average power and near-complete pump absorption.

2. Experimental arrangement

The experimental arrangement for the passively Q-switched laser is shown in Fig. 1. A 6.4 mm x 6.4 mm VCSEL array (Princeton Optronics) consisted of four 2.7 mm x 2.7 mm square quadrants, separated by 1 mm from each other, and wired in series. The VCSELs in each quadrant were arranged in a hexagonal array pattern, and utilized hexagonal-shaped active apertures defined by selective oxidation process for current and optical confinement [1,2]. The array operated at a wavelength of 804 nm, and emitted a peak power (P_p) of 490 W at 170 A. An AR coated, f = 10.5 mm focal length aspheric lens, placed close to the VCSEL array, focused 98% of the pump light into the input face of a 35 mm long, 4.25 mm diameter, Nd:YAG rod (0.8 at.%). The pumped end of the rod had a dichroic HR@1064nm/HT@790-820 nm coating, and the other end had an AR@1064 nm coating. The 6 cm long unstable resonator incorporated a Cr^{4+}:YAG with 45% un-bleached transmission and an R = 70% output coupler with a 5 m convex radius of curvature.

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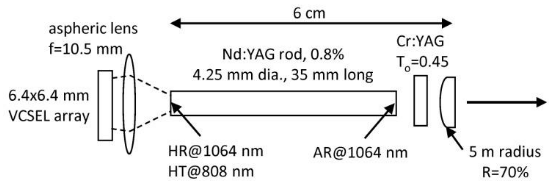

Fig. 1. Experimental arrangement for the passively Q-switched laser.

3. Results and discussion

The laser operated at 5Hz PRF, and generated 3.7 ns to 4.6 ns Q-switched pulses over all the VCSEL array operating currents between 80 A (P_p = 235 W) and 170 A. To characterize the laser performance, we first measured its beam far-field divergence using a Spiricon beam profiler. After using a lens to remove the spherical wavefront component due to the unstable resonator, a beam divergence of 0.45 mRad (full angle) was measured (1/e^2 intensity method). A representative near-Gaussian far field intensity profile is shown in Fig. 2, where VCSEL array current was 130 A (P_p = 395 W).

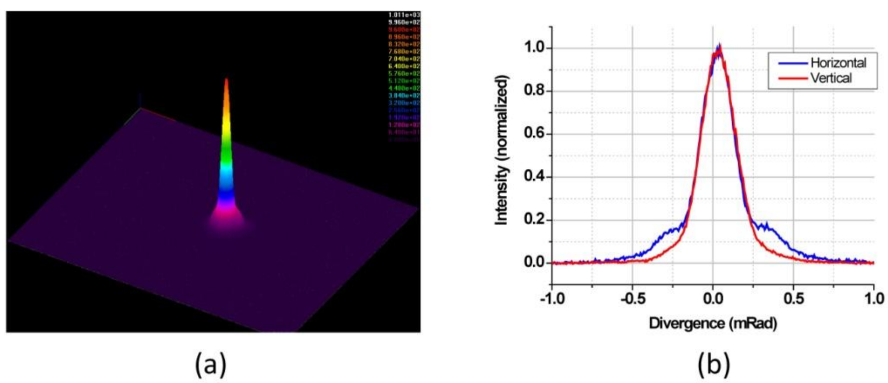

Fig. 2. Q-switched laser angular divergence distribution (a) 3-D color representation, (b) horizontal and vertical line-scans through the center of the distribution.

In a passively Q-switched laser, lasing threshold is reached when laser gain equals the sum of un-saturable and saturable cavity losses, with the output energy being nominally independent of the pump intensity [3–7]; lower pump power simply requires longer pump duration to reach threshold population inversion. When varying the VCSEL current, however, we observed a significant change in the output pulse energy of the laser; this variation is shown in Fig. 3(a). A 2x increase in the pulse energy, from 9 mJ to 18 mJ, was measured when the VCSEL current was increased from 80 A to 170 A. To reach lasing threshold, the pump pulse duration was adjusted from 670 µs at 80 A to 305 µs at 170 A to. The laser's optical efficiency [also shown in Fig. 3(a)], defined as the output energy divided by the pump energy incident on the rod, decreased at low pump powers due to the pump durations that significantly exceeded the 230 µs Nd:YAG fluorescence lifetime.

For comparison, we also pumped the same laser with a conventional 3x3 mm laser diode stack (Lasertel Inc.), consisting of 9 bars that were fast-axis-lensed to reduce their divergence. This arrangement produced a nearly-equal 15° (FWHM) divergence in both planes. As with VCSEL pumping, an f = 10.5 mm lens was used to focus and couple the diode stack emission into the Nd:YAG rod with a coupling efficiency of 88%. As shown in Fig. 3(b), the diode-stack-pumped laser exhibited nearly constant energy output (9.4 mJ-9.8 mJ) for all pump

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powers. The 4% increase in pulse energy was likely caused by similar increase in the diode-bar slow axis divergence.

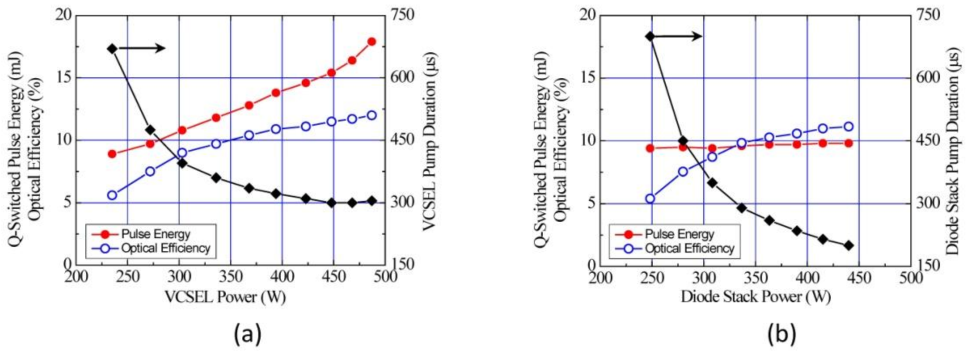

Fig. 3. Comparison of (a) VCSEL pumped laser and (b) diode stack pumped laser showing pulse energy, optical efficiency, and pump duration vs. pump power.

In order to understand laser output energy variation observed with VCSEL pumping, we measured the pump intensity distribution incident on the rod. The intensity distribution at the focal plane of the lens can be described as an incoherent sum of the intensities of the Fourier transforms of the incident field distributions of the individual VCSEL elements. The resulting composite intensity distribution represents the combined angular spectrum of the entire VCSEL array. Neglecting lens aberrations, the focused spot diameter is given by focal length of the lens times the full divergence angle of the VCSEL emission. Figure 4 shows intensity distributions at the lens focal plane for VCSEL currents of 100 A (P_p = 300 W) and 160 A (P_p = 470 W). The hexagonal spot-shape is due to the hexagonal active aperture of individual VCSEL emitters. The superimposed 2.7 mm dashed circle contained 85% and 78% of the total energy, for 100 A and 160 A, respectively, while the larger 4.25 mm circle, equal to the Nd:YAG rod diameter, contained 98% of total energy for both currents.

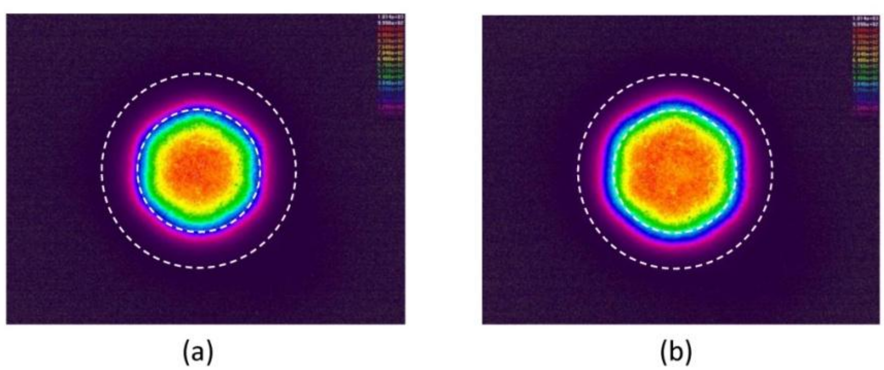

Fig. 4. Intensity distributions at the focal plane of the focusing lens for VCSEL array currents of (a) 100 A, and (b) 160 A.

Figure 5 shows line-scan intensity profiles through the center of the intensity distributions of Fig. 4. High VCSEL current clearly results in a larger size and flatter shape of the pump spot, a consequence of increased divergence of each VCSEL element. Such changes in the VCSEL divergence can be attributed to variation in its multimode spatial mode field profile with current [12–17], caused by current-dependant thermal lensing and local gain suppression at the center of the active aperture due to non-uniform heating [15–17].

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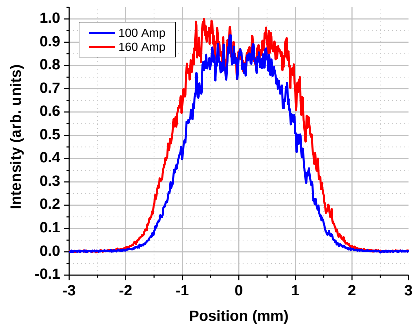

Fig. 5. Line-scan intensity profiles through the center of intensity distributions of Figs. 4(a) and 4(b).

Figure 6 shows the VCSEL near field intensity distributions at 80 A and 160 A (the camera sensitivity was adjusted to normalize the peak intensities). As observed previously [13], the intensity distributions for VCSEL of similar diameter were highly multi-mode and exhibited crowding near the edges of the aperture. No dramatic differences in the intensity patterns between 80 A and 160 A operation were apparent, with higher current resulting in a more complete filling of the emission ring near the aperture edge. Although changes in intensity distributions were small, the VCSEL angular spectrum is also determined by the near field optical wavefront phase profile, which was not measured. For a fixed operating current, no changes in the near field or far field intensity distributions were observed when the pulse duration was varied between 25 μs and 600 μs.

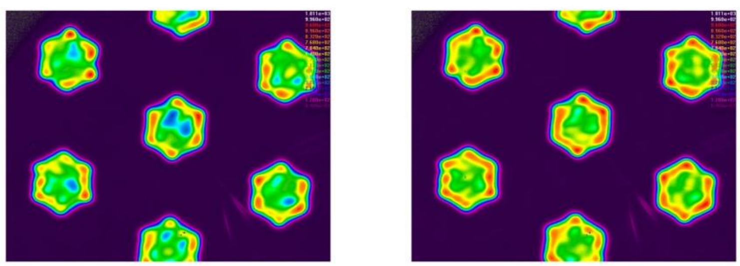

Fig. 6. Normalized near field intensity distributions for VCSEL currents of 80 A (a) and 160 A (b).

The current-dependent changes in the pump spot incident on the Nd:YAG rod were found to cause significant changes in the laser active area. This effect is clearly evident in Fig. 7 showing Q-switched laser near-field profiles, and Fig. 8 showing their line-intensity scans, for VCSEL currents of 80 A, 130 A and 170 A, with all profiles were taken with the same camera settings. The slightly off-center position of the emission is attributed to a small angular misalignment of the output coupler.

Observed changes in the laser near field distributions are consistent with models of passive Q-switching [4,6,7]; the laser gain is expected to first reach threshold condition at the lateral position where the pump intensity is highest, which in our case occurred close to the center of the rod. Since the population inversion and gain at this position are pinned at their lasing threshold values, the near field intensity there remains invariant with changing pump intensity. Increased pump intensity will simply result in a shorter pump duration required for

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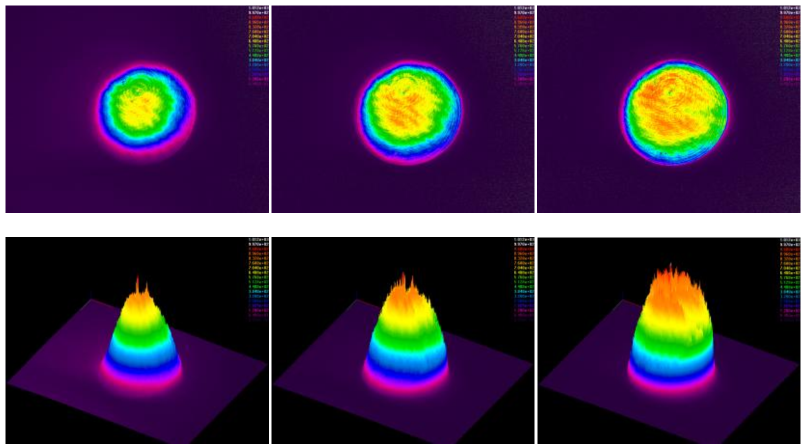
threshold inversion. This behavior is evident in Figs. 7, 8, where the near field intensity at the center of the rod remains relatively constant over pump power range of 235 W to 490 W.

Figure 8 clearly shows that the laser active area increased at larger VCSEL currents; the near field distribution became wider and flatter while the center intensity remained relatively constant. Since the laser output energy is proportional to the total area under the near field intensity distribution, this resulted in increased pulse energy for the higher VCSEL currents.



80 A   130 A   170 A

Fig. 7. Q-switched laser near field intensity profiles for VCSEL currents of 80 A, 130 A and 170 A. The laser pulse energy is 9 and 18 mJ for 80 A and 170 A, respectively.

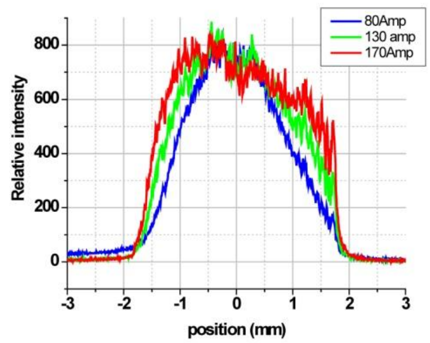


Fig. 8. Line scans (horizontal) through the center of near field intensity distributions of Fig. 7 for VCSEL currents (powers) of 80 A (235 W), 130 A (395 W) and 170 A (490 W).

4. Conclusion

A VCSEL end-pumped, passively Q-switched Nd:YAG laser with adjustable output pulse energy was demonstrated. A single lens was used to couple >98% of the VCSEL array emission into the laser rod. The output pulse energy was adjustable between 9 mJ and 18 mJ by varying the VCSEL operating current. The energy variation was attributed to changes in VCSEL divergence characteristics, which altered the intensity profile of the pump spot incident on the laser rod. Higher laser output energy, increase optical efficiency and wider energy adjustment range are anticipated with increased VCSEL powers, optimization of VCSEL structures and laser resonator designs.

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